



# THORPEX International Science Plan

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**Mission Statement - THORPEX:** a Global Atmospheric Research Programme is an international research programme to accelerate improvements in the accuracy of 1 to 14-day high-impact weather forecasts for the benefit of society and the economy. The programme builds upon ongoing advances within the research and operational-forecasting communities. It will make progress by enhancing international collaboration between these communities and with users of forecast products.

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# CONTENTS

<b>Title Page</b> .....	i
<b>Contents</b> .....	ii
<b>Contributors</b> .....	iii
<b>1. Introduction</b> .....	<b>1 - 4</b>
1.1. Rationale .....	1
1.2. Reference Material .....	4
<b>2. Predictability and Dynamical Processes</b> .....	<b>4 - 11</b>
2.1 Rationale .....	4
2.2 Dynamical Process Studies .....	4
2.3 Predictability Issues .....	6
2.4 Proposed Research .....	8
2.5 References .....	10
<b>3. Observing Systems</b> .....	<b>11 - 16</b>
3.1 Rationale .....	11
3.2 Current and Anticipated Remote and <i>In-situ</i> Observing systems .....	11
3.3 Observing-System Simulation Experiments (OSSEs) .....	14
3.4 THORPEX Observing-System Tests, Regional Campaigns, and the Global Prediction Campaign .....	14
3.5 Proposed Research .....	15
3.6 Reference Material .....	16
<b>4. Data Assimilation and Observing Strategies</b> .....	<b>16 - 22</b>
4.1 Rationale .....	16
4.2 Targeting strategies .....	17
4.3 Improved use of observations .....	18
4.4 Adaptive data assimilation .....	19
4.5 Proposed Research .....	20
4.6 References .....	22
<b>5. Societal and Economic Applications</b> .....	<b>22 - 26</b>
5.1 Rationale .....	22
5.2 Societal and Economic Benefits of Weather-Forecast information .....	23
5.3 Proposed Research .....	24
5.4 Reference Material .....	26

## CONTRIBUTORS

This document was prepared with input from across the international atmospheric science community. It draws on material from the September 2001 [THORpex Proposal](#), the first meeting of the International Science Steering Committee (ISSC) in March 2002, the [THORpex Status Report](#) issued in July 2002 following the first International THORpex Workshop in March 2002, the THORPEX Overview Document issued in September 2002, the first and second meetings of the International Core Steering Committee in October 2002 and April 2003, the second International THORPEX Workshop, the Asian/THORPEX Mini Workshop in October 2002, the second meeting of the ISSC in December 2002 and various WMO (CAS, WWRP and WGNE) committee meetings in 2001 and 2002. This document, and other background material about THORPEX, can be found on the THORPEX web site: <http://www.wmo.ch/web/arep/wwrp/THORPEX/THORPEX.htm>

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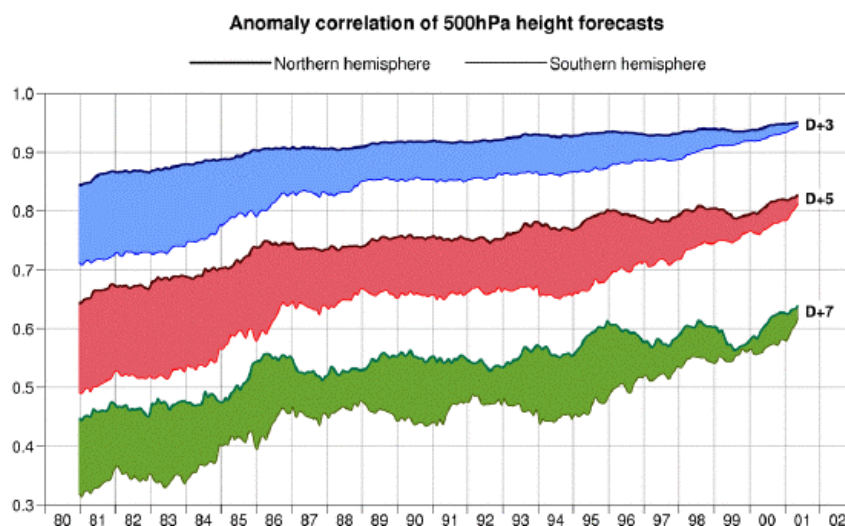
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# 1. Introduction

## 1.1 Rationale

The success of numerical weather prediction represents one of the most significant scientific, technological and societal achievements of the 20<sup>th</sup> century. Despite the notable increase in forecast skill over the past quarter century (Fig.1.1), there is a necessity for further improvements, particularly, in high-impact weather forecasts and in the use of weather information. High-impact weather forecasts are defined by their effect on society and the economy. They are typically associated with forecasting cyclones of extratropical and tropical origin that contain significant embedded mesoscale weather, such as localized flooding by convective and orographic precipitation; blizzard snows; destructive surface winds; dust-storms. They also encompass meteorological conditions affecting air quality, periods of anomalous high/low temperature and drought, and non-extreme weather with high-societal impact. Improving the skill of high-impact weather forecasts is one of the great scientific and societal challenges of the 21<sup>st</sup> century. THORPEX is a response to this challenge.

### Evolution of forecast skill for northern and southern hemispheres



**Fig. 1.1:** Evolution of forecast skill for the northern and southern hemispheres: 1980-2001. Anomaly correlation coefficients of 3, 5, and 7-day ECMWF 500-mb height forecasts for the extratropical northern and southern hemispheres, plotted in the form of running means for the period of January 1980-august 2001. Shading shows differences in scores between hemispheres at the forecast ranges indicated (from Hollingsworth, *et al.* 2002).

Emerging developments in atmospheric science and technology provide the opportunity for dramatic improvements in weather forecasts and in their use and value to society. These developments include: i) advances in the knowledge of the theoretical and practical limits of atmospheric predictability, including the influence of inter-annual and intra-seasonal climate variability on forecast skill; ii) expanding observations of the Earth System with satellite, airborne, marine and land-based observing technologies; iii) weather forecast systems capable of assimilating observations from the above diverse technologies; iv) advanced forecast procedures aided by improvements in numerical techniques, parameterised and explicit representations of physical processes, ensemble forecast techniques, and exponential increases in the speed and memory of supercomputers; v) innovative approaches to the

design and implementation of forecast systems that optimise the societal and economic utilisation of weather information. In the same way that the atmosphere encompasses the globe, the expertise to exploit and further these advances resides across many nations, international organisations, and different scientific disciplines.

THORPEX establishes a contemporary organisational framework to address global weather research and forecast problems whose solutions require international and academic-operational collaboration. This will include engagement with other international programmes within the World Meteorological Organisation (WMO), the International Council of Scientific Unions (ICSU) and the Intergovernmental Oceanographic Commission (IOC). In this regard, THORPEX aspires to be the second Global Atmospheric Research Programme (GARP); building on the accomplishments of the First GARP Global Experiment (FGGE).

THORPEX is developed and implemented as a part of the WMO World Weather Research Programme (WWRP). The international co-ordination for THORPEX has been established under the auspices of the WMO Commission on Atmospheric Sciences (CAS) through its Science Steering Committee for the WWRP, and joint CAS/JSC Working Group on Numerical Experimentation (WGNE). The THORPEX International Science Steering Committee (ISSC) establishes the core research objectives with guidance from the THORPEX International Core Steering Committee (ICSC) whose members are nominated by Permanent representatives of countries with the WMO. Research objectives are developed under four Sub-programmes: *Predictability and Dynamical Processes*; *Observing Systems*; *Data Assimilation and Observing Strategies*; *Societal and Economic Applications*. These Sub-programmes have the responsibility to: i) coordinate the research activities envisaged in the THORPEX International Science and Research Implementation Plans; ii) collaborate with other international programmes when relevant expertise is required and mutual benefit is derived. Nations and consortia of nations have established Regional Committees that define regional priorities for participation in THORPEX within the framework of the THORPEX International Science and Research-Implementation Plans.

The core research objectives of THORPEX are to:

- Contribute to the design and demonstration of *interactive forecast systems* that allow information to flow interactively between forecast users, numerical forecast models, data-assimilation systems and observations. Interactive forecast systems include the new concept of targeted observations, referred to as *targeting*. Targeting incorporates dynamical information from the numerical forecast model itself to identify when, where, and what types of observations would provide the greatest improvement to specific weather forecasts.
- Advance the knowledge of global-to-regional influences on the initiation, evolution, and predictability of high-impact weather. This will include research into: i) the degree to which predictive skill is limited by observations, data assimilation, model uncertainty, or ensemble prediction system design at various forecast lead-times; ii) the excitation of Rossby wave-trains by extratropical cyclogenesis, large-scale topography, continent/ocean interfaces, and organised tropical and extratropical convective flare-ups, and the consequent initiation of high-impact weather; iii) the dependence of predictive skill on inter-annual and intra-seasonal climate variability, e.g., El Nino Southern Oscillation (ENSO); Pacific North-Atlantic oscillation (PNA); North-Atlantic Oscillation (NAO); monsoon circulations.

- Collaborate with numerical forecast centres in the development of advanced data-assimilation and forecast model systems. Research will include: i) improving the assimilation of existing and experimental observations, including observations of physical processes and atmospheric composition; ii) developing adaptive data-assimilation and targeted-observing strategies; iii) incorporating model uncertainty into data-assimilation systems and in the design of ensembles.
- Develop and apply new methods to enhance the utility of improved weather forecasts through: i) the use of new user-specific probabilistic forecast products; ii) the introduction of interactive procedures that make the forecast system more responsive to user needs; iii) the design of and training in the use of user-specific forecast products. This research will identify and assess the societal/economic costs and benefits of THORPEX recommendations for implementing interactive forecast systems and improvements in the global observing system.
- Perform THORPEX Observing-System Tests (TOSTs) and THORPEX Regional field Campaigns (TReCs). TOSTs will: i) test and evaluate experimental remote-sensing and *in-situ* observing systems, and when feasible, demonstrate their impact on weather forecasts; ii) explore innovative uses of operational observing systems. TReCs are quasi-operational forecast demonstrations contributing to the design, testing and evaluation of all components of interactive forecast systems. They will be organised and coordinated by regional consortia of nations under their respective THORPEX Regional Committees (European, Asian, North-American, and Southern Hemispheric) TReCs will address regional high-impact weather events, e.g., arctic storms and cold-air outbreaks; cool-season extratropical cyclones over Europe, Asia, and North America; warm-season heavy precipitation over Asia; organized equatorial convection flare-ups; tropical-to-extratropical cyclone transformations.
- Demonstrate the full potential of THORPEX research results for improving operational forecasts of high-impact weather on time-scales out to two weeks. This demonstration includes the ***THORPEX Global Prediction Campaign (TGPC)***. The TGPC will: i) deploy and/or activate the full suite of experimental and operational observing systems over the globe for a season to one year; ii) establish the utility of interactive forecast systems to improve the utility of weather forecasts and user products; iii) provide guidance, through the WMO/World Weather Watch (WWW) to agencies responsible for optimising the design and implementation of the fixed and adaptive components of the existing regional and global observing systems; iv) coordinate the transfer and application of THORPEX research and operational results to developing countries.

THORPEX is unique, in that:

- It establishes an organisational framework that addresses today's global weather research and forecast problems whose solutions require international and academic-operational collaboration. Its research domain spans global-to-regional influences on the prediction of high-impact weather. It considers those mesoscale weather systems that form in response to the larger-scales and not those arising from purely local influences.

- It has at its heart, the contemporary paradigm in which weather forecasting is addressed as an *interactive* system with information flowing between forecast users, forecast models, data assimilation and global and regional observing systems.
- It will conduct regional and global campaigns as demonstrations and assessments of new observing technologies and interactive forecast systems. Thereby, THORPEX will provide guidance to the World Weather Watch and forecast centres on improvements to forecast systems, and to the relevant bodies, such as the WMO Commission for Basic Services Open Programme Areas Group, concerning optimisation of global and regional observing-systems.
- It addresses the influence of intra-seasonal time scales on week-two high-impact forecasts, and therefore aspires to bridge the “middle ground” between medium-range weather forecasting and climate prediction. This provides a link with other programmes addressing the improvement of global climate-change prediction systems.

## 1.2 Reference Material

Hollingsworth, A., Viterbo, P., and A. J. Simmons. 2002: The relevance of numerical weather prediction for forecasting natural hazards and monitoring the global environment. ECMWF Technical Memorandum No. 361, pp. 29.

U.S Committee for the Global Atmospheric Research Program, Division of Physical sciences, National Research Council, 1969: National Academy of Sciences, Washington, D. C., 79 pp.

## 2. Predictability and Dynamical Processes

### 2.1 Rationale

THORPEX predictability and dynamical-processes research will consider those aspects of the atmosphere and numerical forecast systems that contribute to limitations on predictive skill for forecasts ranging from 1 to 14 days. Questions are often posed regarding the spatial and temporal limits of predictability and what determines these limits. Clearly, the limits of predictability depend on attributes of the atmosphere that are being forecast, because certain properties of the global weather exhibit some degree of predictability over particular time ranges, such as: i) the global-mean surface temperature exhibits a degree of predictability over time-scales in excess of centuries; ii) monthly-mean temperatures over particular regions are thought to be predictable over time-ranges of seasons to decades; iii) individual synoptic-scale weather systems do have predictability out to 7 days, including their associated sub-synoptic-scale high-impact weather. THORPEX will assess the various factors that contribute to current limits of predictability for appropriate forecast attributes and through this determination develop and demonstrate new dynamical interpretations, and observing-system and forecasting strategies that reduce these limitations.

### 2.2 Dynamical Process Studies

THORPEX dynamical processes research aims to advance basic knowledge of global-to-regional influences on the evolution and predictability of high-impact weather. A basic premise is that there exists a class of regional high-impact weather events and their forecasts

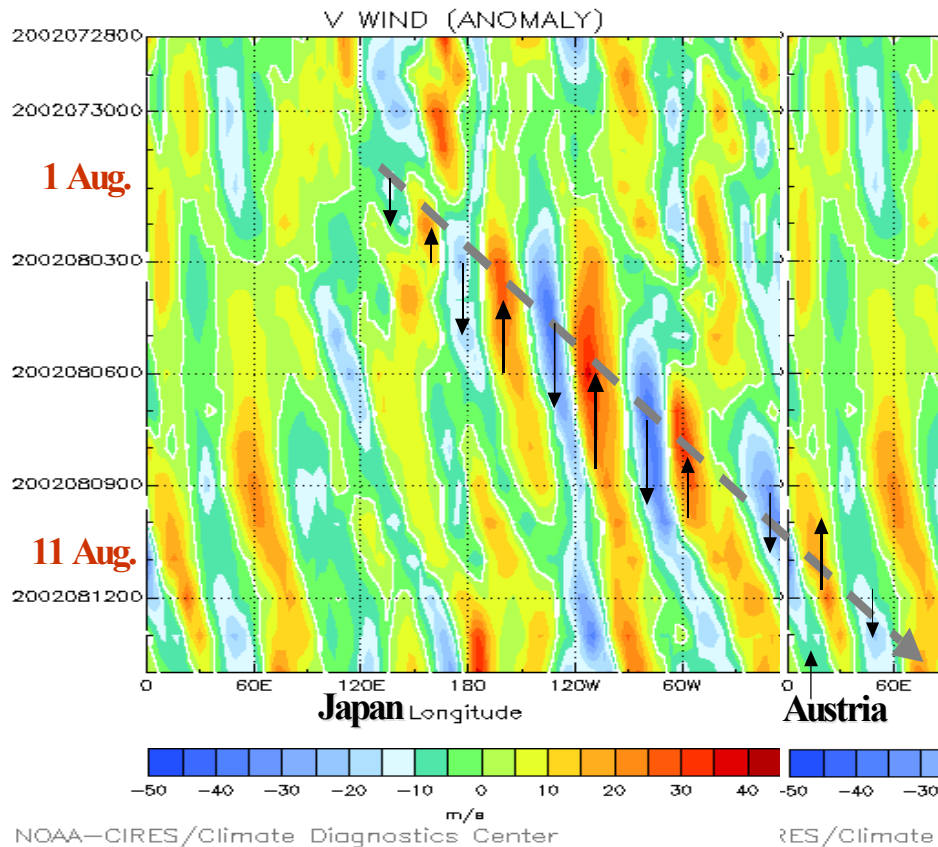
that develop within the context of the larger-scale motions. This includes: i) extratropical cyclones, their storm tracks and predictive skill that are modulated by anomalies in seasonal and intra-seasonal time-mean flows; ii) extratropical cyclones that form by downstream baroclinic development associated with larger-scale Rossby wave trains (wave packets) that occasionally encircle the earth in about 12 days (Chang and Yu 1999); iii) fronts and their associated mesoscale precipitation systems that form in response to synoptic-scale deformations within synoptic-scale extratropical cyclones; iv) extreme mesoconvective precipitation systems that form where the synoptic-scale flow brings together contrasting air masses, such as at the Mei-Yu (Baiu) front, arctic front, and “Spanish plume”; v) tropical cyclones circulations that are transformed into extratropical cyclones through interactions with synoptic-scale waves in the extratropical westerlies (Thorncroft and Jones 1995). In addition, predictability and dynamical process research will consider the evolution of intra-seasonal and inter-annual phenomena, so as to capture and exploit the significant dependence of the predictive skill of high-impact weather on large-scale influences, such as, the phases of the MJO, ENSO, NAO. This represents a major linkage between weather and climate dynamics and their prediction.

In order to address the above issues, THORPEX dynamical-process research will consider concepts such as: i) Rossby wave trains and their relationship to the propagation of forecast error; ii) the potential vorticity (PV) perspective of high-impact weather forecasts and of sensitive regions, that lead to forecast error growth.

**Rossby wave trains:** The excitation and dispersion of Rossby wave trains represents an example of the global propagation of a localized influence on high-impact weather and its prediction. The skillful prediction of Rossby wave-train activity is often a requisite for forecasting the synoptic-scale setting within which smaller-scale, high-impact weather events evolve at forecast time ranges out to two-weeks. Rossby wave trains are initiated by components of the flow, such as: i) downstream baroclinic development (Orlanski and Sheldon 1993); ii) the interaction of extratropical flows with large-scale topography, e.g., the Tibetan Plateau; Greenland; iii) moist tropical convective-heating variations associated with the El Niño Southern Oscillation (ENSO), the Madden Julian Oscillation (MJO), and higher frequency convective variability within the oceanic convergence zones and monsoon regions, which produce subtropical Rossby wave source regions from which Rossby wave energy disperses into the extratropics. The group velocity at which Rossby wave trains propagate is equivalent to the propagation velocity at which forecast errors spread downstream from an initially localized region of initial-condition error. Both Rossby wave trains and forecast error can circumnavigate the hemisphere at 45 N. in ~12 days, as was the case for the wave train initiated by downstream baroclinic development shown in Fig. 2.1.

**The potential vorticity perspective:** Potential vorticity distributions characterize those quasi-balanced dynamical features that are most potent in the development of synoptic-scale weather systems. Potential vorticity is useful for identifying and tracking *centres of action* because of its various dynamical properties, such as: i) conservation (in certain cases); ii) non-conservation due to irreversible physical processes; iii) invertibility. The use of *conservation* and *invertibility* to infer the dynamics of quasi-balanced flows is known as *PV thinking*. Diagnosing forecast-model behaviour in terms of PV can be a powerful tool for isolating key uncertainties in the representation of dynamical and physical processes, when the magnitude of the PV uncertainty is sufficiently large in comparison to the background PV. Recent studies have suggested that certain types of initial-condition uncertainties, associated with appreciable forecast error growth, are up-shear-tilted PV structures that are initially maximized in the lower to mid-troposphere, with magnitudes comparable to typical

variations in the tropospheric PV (e.g., Reynolds et al. 2001). Issues to be addressed using PV dynamics include those associated with the: i) extratropical transition of tropical cyclones; ii) PV structure of singular vectors and other growing perturbations; iii) creation of regions of instability that provide the envelope for localized severe weather; iv) the PV perspective of Rossby wave trains; v) flare-ups of tropical convection associated with Rossby wave energy and associated PV perturbations propagating from the extratropics into low latitudes (Kiladis 1998). There is likely to be a strong complementarity between Rossby wave and PV perspectives.



**Fig. 2.1:** Hovmöller (time-longitude) diagram of the 250-mb meridional wind component ( $\text{ms}^{-1}$ ) for the period 28 July - 14 August 2002 and the latitudinal belt 40-60° N. Extreme flooding in central Europe occurred at the end of this period. A Rossby wave train was excited by cyclogenesis off Japan, followed by rapid downstream development of high-amplitude Rossby waves, culminating in the severe weather in Europe. A forecast of the cyclogenesis east of Japan is necessary to obtain skillful medium-range forecasts over Europe.

## 2.3 Predictability Issues

### *Uncertainty in numerical weather prediction*

Factors that contribute to uncertainty in numerical weather prediction are: i) *uncertainty in the physical laws* governing atmospheric motions, notably in the numerical approximations used for their solution and the parameterizations of the unresolved (sub-grid) motions; ii) *uncertainty in the forecast initial conditions* arising from systematic and random errors in the observations, inhomogeneity in the spatial/temporal coverage of observations, representativeness of a given observing system to the spatial/temporal scales resolved by the forecast model, and approximations in data assimilation systems (Thompson 1957). Factors i) and ii) are referred to as *model uncertainty* and *initial condition uncertainty*, respectively. It is believed that the largest contribution to short-range forecast error is associated with initial-

condition uncertainty; whereas both initial condition and model uncertainty contribute to forecast uncertainty at extended time ranges (Lorenz 1990). It is important to note that a forecast system with zero uncertainty in the forecast model or initial conditions will possess residual uncertainty, here referred to as the *intrinsic uncertainty*, produced by the unresolved motions that are independent of the motions resolved by the forecast model. This intrinsic uncertainty results from finite model resolution dictated by limitations in computational resources. THORPEX predictability research will address the relationship between model uncertainty, initial condition uncertainty and the construction of ensemble prediction systems with the aim of producing forecasts with skill limited only by the intrinsic uncertainty.

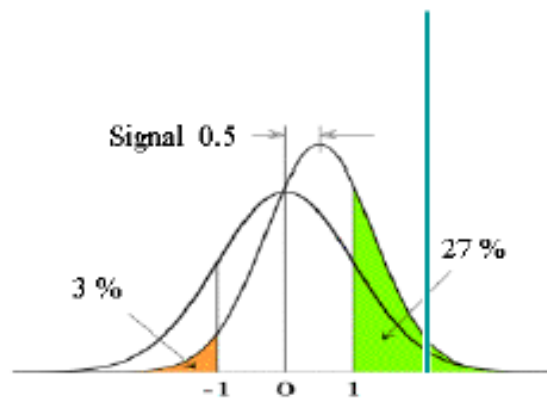
### ***Ensemble weather-prediction***

Developments in numerical weather prediction have led to current forecast systems that use an *Ensemble Prediction System* (EPS) to assess the probability of occurrence of possible forecast outcomes (Palmer 2000 and references therein). An EPS is a collection of individual forecasts (*forecast members*) made from slightly different initial conditions and/or model formulations. The *spread* of the forecast member outcomes, defined as the *standard deviation* of the members from the *ensemble mean*, gives an estimate of EPS uncertainty. Estimates of the forecast uncertainty, for any forecast variable at any geographical location, are described by the *probability density function* (PDF) produced by a frequency distribution based on the various ensemble members.

Ensemble weather prediction can be described as a process leading to the computation of the *conditional probability distribution*, which is the PDF obtained from a forecast system conditional upon using a specific forecast model and its initial conditions, and thereby on the observations and the data assimilation system. The PDF is initially narrow at the start of the forecast, with the initial spread of the ensemble members reflecting the likely uncertainty in the analysis. As the forecast lead-time increases, the chaotic growth of initially small perturbations leads to forecasts becoming increasingly uncertain and predictability for the small scales is lost within a relatively short time, with a subsequent loss of predictability for the larger spatial scales. A skillful EPS aims to capture the evolution of this PDF. Hence, the PDF will vary with location and time, so that, for example, day-two forecast uncertainty is likely to be larger for a developing cyclone than for a quasi-static anticyclone. For an EPS to be skillful, the PDF must possess two properties: i) it must encompass the weather that actually occurs, i.e., the verifying observations, and ii) at forecast lead times shorter than the predictability limit, it must be either narrower or with a different mean (or both) than the climatological, or unconditional probability distribution appropriate to the particular meteorological situation (Fig. 2.2). If the forecast PDF possesses the above properties, then the forecast is more skillful than the appropriate climatology. Further improvement in EPS skill will be derived from research leading to forecast systems in which: i) the forecast PDF is as narrow as possible; ii) its ensemble-mean is, on average, as close as possible to the verifying analysis.

As noted above, the intrinsic uncertainty produced by the unresolved motions that are independent of the motions resolved by the numerical model, results from finite model resolution dictated by limitations in computational resources. The forecast PDF implied by this intrinsic uncertainty defines what is sometimes called the *potential predictability* of the system. The difference between the actual forecast and that associated with the potential predictability defines the scope for improving the forecast skill by reducing the above uncertainties and improving computational power. THORPEX is devoted to carrying out research to reduce this difference.

In summary, ensemble forecast members should reflect the range of uncertainty in the numerical model, the data assimilation algorithm and the initial conditions. Current operational EPSs do not fully address all sources of forecast uncertainty because: i) the ensemble initial conditions do not adequately sample the distribution of possible analysis states; ii) the effect of un-parameterized unresolved variability on the resolved scales is neglected or misrepresented; iii) model uncertainties, especially those associated with parameterizations, are not properly accounted for. Research is underway to address these issues, but currently most effort has been devoted to initializing ensembles using initial conditions within a range of uncertainty arising from instrumental error characteristics and observational representativeness error. Some operational centers, such as the Meteorological service of Canada (MSC) and European Centre for Medium-range Weather Forecasts (ECMWF) currently incorporate model-uncertainty components into their ensemble forecast systems (e.g., Barkmeijer et al. 2003). THORPEX is dedicated to improving estimates of the forecast PDF through research on all sources of forecast uncertainty.



**Fig. 2.2:** Schematic probability density functions illustrating the climatology (with zero mean), and the forecast PDF (displaced from zero mean) at some forecast lead time, evolved from an initially narrow PDF (blue vertical line). For the EPS to be reliable, the verifying analysis at that lead time must fall within the climatology. The coloured areas indicate the chances of the verifying analysis falling at the extremes of the climatology, which are substantially different from the 16% chance expected from climatology.

## 2.4 Proposed Research

THORPEX aims to advance knowledge in atmospheric predictability and the underlying dynamical processes required for the development of effective, integrated forecast systems that: i) identify the user-needs, ii) select and assimilate those observations most relevant to a particular forecast objective, and thereby iii) generate highly skillful probabilistic forecasts and end-user products. This will include research that will:

**Investigate the effect of dynamical and physical processes on forecast skill:** Research will address dynamical and physical process operating on various scales that contribute to errors in high-impact forecasts. Studies of Rossby wave excitation and subsequent dispersion will consider: i) the skill of forecast systems in predicting Rossby wave amplitudes, ray-paths and group velocities; ii) the initiation of wave-trains by tropical convection, extratropical cyclones and large-scale topography; iii) the initiation of tropical convection by Rossby wave-trains propagating from extratropics into the tropics; iv) the influence of physical

processes, both parametrised and explicit, on the prediction of Rossby waves and their dispersion. Coherent structures, such as discrete anomalies of PV, and the extratropical transition of tropical cyclones, will be investigated. Assessments will be made of the role of global teleconnections, e.g., tropical-extratropical interaction, including the factors involved in their initiation and predictability.

**Determine the influence of flow regimes on the climatology of forecast skill:** THORPEX will assess the intra-seasonal and inter-annual variability in the climatology of forecast error, ensemble spread and the distribution of observationally-sensitive regions. This includes determining the dependence of these climatological variabilities on flow regimes, such as: i) zonal or blocked states, and ii) phases of prominent phenomena and major teleconnections, e.g., MJO, PNA, ENSO and NAO. The impacts of such flow regimes and their variability on Rossby wave propagation, dispersion and predictability will be investigated. The skill of EPS forecasts will vary depending on the meteorological situation. For example, the skill in predicting extratropical cyclones in the Pacific sector may differ substantially depending on the phase of ENSO (e.g., Shapiro et al 2000). This is referred to as *regime-dependent evaluation* of forecast skill. THORPEX aims to fully explore the analysis of this regime dependence, as this will provide substantial input to improve EPS design.

**Assess predictive skill at all forecast ranges, including potential predictability:** Key questions concern what are the limitations of predictability and what determines these limitations. THORPEX aims to address these issues, including an assessment of the various limitations of predictability appropriate to defined forecast attributes, and through this assessment explore new forecasting strategies to reduce these limitations. Improved methods of generating ensembles will be used to investigate potential predictability, under the perfect model assumption, utilizing state-of-the-art operational forecast models to assess the potential for further improvements in predictive skill.

**Quantify the contributions of initial condition and model uncertainty to forecast errors:** Developing interactive forecast systems depends critically on having accurate estimates of the sources of forecast error attributable to initial condition uncertainty and forecast-model uncertainty. Research will quantify the influence of all sources of forecast error and their associated mechanisms for growth, on different space and time scales and for different variables and different meteorological phenomena. This includes the uncertainty associated with numerical schemes and physical parameterizations. Improved estimates of the relative contribution of the various sources of forecast error growth will lead to improved probabilistic forecasts and products.

**Investigate the relative effects of small and large-scale initial-condition uncertainty:** Forecast errors can grow rapidly upscale from initial uncertainties in the small-scale motions. However, the analysis and forecast uncertainty is dominated by the slower-growing, but far more energetic, larger-scale motions. THORPEX will address the relative roles of these two sources of initial uncertainty in limiting forecast skill. This will provide guidance for the design of improved observation systems and observing strategies, i.e., should observations be targeted in localized regions of rapid forecast error growth, or is the reduction of initial uncertainty at the larger scales preferable through dispersing finite observation resources over broader areas?

**Develop improved ensemble-prediction systems:** Improved ensemble perturbations are required to accurately represent uncertainty in all aspects of the initial state, including land and ocean surface conditions. Advanced methods must be developed to account for the effect

of un-parameterized, unresolved phenomena on the resolved scales in ensemble forecast systems. Formulations are required to include uncertainties in forecast model formulation, including numerical errors and parameterization errors, in forecast ensembles (these may include investigations of multi-model and multi-parameter ensemble prediction methods, as well as stochastic parameterizations). Prior research has indicated that there may be some useful additional ensemble spread contributed by multi-model or multi-parameterization ensembles. However, these techniques are mostly *ad-hoc*, and it is not clear if their benefit is from the variety of forecast models or the variety of initial conditions provided by different forecast systems. Additional research will determine the potential applications of multi-model ensembles.

The parameterisation schemes in present-day forecast models were designed to give the best possible single forecast and not an ensemble. This is a fundamental problem, since many of these schemes (e.g., those representing turbulent diffusion by unresolved sub-grid processes or convective instabilities) have a stabilizing effect on the resolved larger scales, even though the process acts as a forcing in nature. Hence, another presumably more desirable approach involves developing parameterisations that are stochastic, i.e., time tendencies in the models that include a random component.

**Determine the degree of intra-seasonal predictive skill:** Studies suggest that there is predictive skill in forecasting weekly averages several weeks ahead. Much of this skill can be achieved by simple linear, stochastically-forced inverse models of the extratropical circulation and tropical heating variations derived from their observed simultaneous and lag-correlation statistics (e.g., Winkler et al 2001). Such models have been shown to be competitive with operational forecast models at 2-3 week forecast ranges. Results from using these inverse models show that extratropical weekly averages are predictable only about two weeks ahead if the influence of tropical heating is ignored, but might be predictable as far as six weeks ahead, in some locations, if that influence were properly taken into account. This suggests that 2-3 week forecast skill could be improved by including predictions of the evolution of sea-surface temperature anomalies. Further research will address how much of the predictability in the linear inverse model is associated with growing singular vectors of the empirically-determined system propagator. Research is also required to determine whether such singular vectors could be used for targeting of observations in climatologically critical regions to improve forecasts with lead times of up to two weeks. Reconfiguration of regional observing systems will require longer lead-times than for localized targeting for short-range forecast applications.

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### 3. Observing Systems

#### 3.1 Rationale

It is recognized that weather-forecast skill is inextricably linked to the accuracy and coverage of global and regional observations. THORPEX observing-system research is a response to the requirement for improved observations of the Earth System leading to accelerated advances in the skill of high-impact weather forecasts on time ranges out to two weeks. This research will: i) test and demonstrate innovative airborne and surface-based technologies for deploying *in-situ* upper-air sounding sensors and surface observations; ii) test and calibrate aircraft-borne next-generation space-based remote-sensing systems; iii) test and calibrate newly deployed satellite-based observing systems and develop advanced methods for data extraction; iv) collaborate with data-assimilation and observing-strategies researchers on: a) the assimilation of new observations, to include data characterization, quality control, and data thinning, b) the design of Observing-System Simulation Experiments (OSSEs) and Observing-System Experiments (OSEs) to provide an assessment of the potential impact of emerging observing systems on forecast skill; v) coordinate the logistics of THORPEX observing-systems tests, regional field campaigns and global field campaigns. These efforts will contribute to the demonstration and evaluation of the impact of advanced observing systems in interactive forecast systems.

This Section opens with an overview of *Current and Anticipated Remote and in-situ Observing systems*, followed by discussions of *Observing-System Simulation Experiments*; *THORPEX Observing System Tests*, *THORPEX Regional Campaigns*, *the THORPEX Global Prediction Campaign*; *Research Objectives*.

#### 3.2 Current and Anticipated Remote and *In-situ* Observing Systems

##### Satellite observing systems

Geostationary satellites, and low-earth-orbiting polar and non sun-synchronous satellites provide space-based remote-sensing observations of the atmosphere and earth's surface at wavelengths spanning the ultra-violet, visible, infrared, and microwave bands of the electromagnetic spectrum. These observations include passive and/or active sensing

measurements of radiance, depending upon the spectral band. These measurements are used to derive images, winds, precipitation, land and ocean-surface geophysical and biological characteristics, and atmospheric vertical profiles of geophysical parameters and composition properties. In addition, satellites provide passive and active remote-sensing observations of the meteorological, geophysical, and biological characteristics of land and sea surfaces.

The key observational characteristics of current and developing satellite-based observing systems are summarized as follows:

***Infrared sounders and imagers:*** The spectral resolution of infrared sounders has increased from sensing a limited number of broad spectral regions to over 2,500 very narrow spectral bands. This new *hyper-spectral sounder capability* on polar-orbiting and geostationary satellites will provide observations that resolve temperature and water-vapour distributions with far greater vertical resolution than current sounders. These observations can be attenuated by the presence of clouds. Hyper-spectral sounders are expected to provide improved water-vapour-tracked wind observations through higher-resolution water-vapour profiles. In cloud-free areas, they should provide very accurate surface temperature measurements. Over the next decade, advanced infrared sounders and imagers will increase the number of satellite observations available to operational NWP by a factor of  $10^5$ .

***Microwave sounders and imagers:*** In contrast to infrared sensors, passive microwave sensors can provide observations within and beneath cloudy regions. These observations are used to derive: i) thermodynamic soundings with high-horizontal resolution in cloudy areas; ii) sea-surface winds; iii) cloud properties; iv) spatial coverage of precipitation and its intensity. Though the vertical resolution of microwave soundings is limited when compared to soundings derived from infrared observations, they provide valuable thermodynamic information in regions opaque to infrared sensors, e.g., within and beneath dense cloud layers, which are often regions of dynamical importance.

***Active remote sensing:*** The next-generation of satellite-based active remote-sensing technologies will provide high-vertical resolution measurements of precipitation, cloud, water vapour, ozone, aerosols, and potentially other atmospheric constituents and even atmospheric motions. These technologies include: i) radars measuring reflectivity profiles of cloud, precipitation, and microphysical properties; ii) Doppler radars measuring air motions within clouds and precipitation; iii) advanced scanning lidars providing images and profiles of backscatter, differential-wavelength absorption, winds, reflectivity and measuring both atmospheric composition and winds. These emerging observing technologies hold unexplored potential for numerical weather prediction applications, by providing improved accuracy of cloud-top height assignment, constituent track winds, improvements of the characterization of model physics, or even direct measurement of airflows with Doppler measurements. In addition, microwave passive sensing from a constellation of satellites can be combined with active dual-wavelength radar observations from a core satellite to improve both the frequency and accuracy of precipitation measurements from space.

***GPS Met:*** Radio-frequency signals from Global Positioning Satellites (GPS) can be used to obtain thermodynamic observations of the atmosphere. Surface-based receivers of GPS signals are used to derive vertically integrated water vapour and receiver-to-satellite measurements of atmospheric refractivity. Satellite-to-satellite signal transmission provides vertical profiles of atmospheric refractivity through active limb scanning, when signals from individual satellites within a constellation of GPS satellites undergo occultation by the atmosphere. The radio occultation technique provides: i) high-vertical resolution profiles of

refractivity that are not severely affected by clouds or precipitation; ii) a global data set of electromagnetic energy travel time through various layers of the atmosphere that does not require calibration; iii) errors that are statistically independent of other types of satellite radiance measurements.

### **New technologies for deploying in-situ sounding systems and surface observations**

The Observing Systems Sub-programme will participate in the development and demonstration of new techniques for deploying in-situ profiling systems (e.g., radiosondes; dropsondes) and expanded surface observations. This effort stems from the requirement for improved coverage of in-situ observations in remote regions where: i) conventional radiosondes are difficult and/or costly to deploy, e.g., over oceans and polar regions; ii) satellite observing systems have reduced capabilities, such as within and below cloud layers opaque to infrared and visible sensing from space; iii) in polar latitudes, geostationary satellites provide limited observational coverage. These advanced deployment systems include:

***Surface deployments of upper-air sounding systems:*** Recent technological advances for surface deployments of *in-situ* sounding systems include Bi-directional Radiosondes and Rocketsondes. Bi-directional Radiosondes provide both ascent/descent GPS radiosonde technology soundings. The Rocketsonde soundings are taken by a GPS dropsonde deployed after a surface-launched rocket reaches its maximum height of ~8 km. Rocketsondes could be deployed from ships, land, sea-ice at fixed times or eventually upon demand. In addition, the expansion of the Automated Shipboard Aerological Programme (ASAP) allows for radiosonde deployments from ocean-going merchant ships. New sensors for conventional radiosondes may also allow accurate measurements of water vapour in the upper troposphere.

***Stratospheric balloons and aircraft deployments of dropsondes:*** Technological advances in balloon materials, global communications, and *in-situ* profiling sensors have revived interest in stratospheric-balloon deployments of upper-air soundings. Current advances include the development of zero-pressure balloons that carry a payload of ~20 dropsondes. Dropsonde carrier balloons travel for ~5 days at or above 100 mb and deploy dropsondes that provide high-vertical-resolution profiles of atmospheric temperature, pressure, humidity and wind, at scheduled times/locations or on-demand. Advances in dropsonde technology will soon allow dropsondes to be deployed from commercial aircraft, using technology that is currently in operational use in the NOAA/Winter Storm Reconnaissance (WSR) program, and NOAA and US Air Force Hurricane-Hunter surveillance programme.

***Constant flight-level and vertical profiling observations from aircraft:*** New technology has led to improvements in the quality and increases in the quantity of flight-level meteorological measurements from passenger, cargo aircraft and Aerosondes. The installation of *in-situ* observing systems on regional-commuter, freight and general-aviation aircraft permit soundings to be made more widely, such as in remote regions where operational radiosondes are difficult to deploy, and in areas distant from major continental and trans-continental air routes. *In-situ* sensors may be miniaturized and suspended in air currents for weeks, such that when deployed from aircraft and balloons in large numbers, they would provide extensive observational coverage of the earth. *In-situ* observations can also be made along horizontal air trajectories from super-pressure constant-level balloons. The development of “smart” balloons that can be steered towards observationally sensitive regions would be advantageous. Airborne lidar and radar instruments provide even greater capabilities, albeit at greater cost.

**Surface in-situ observations:** The geographical coverage of surface *in-situ* observations has improved dramatically over the last decades. For example, the expansion and deployment of automatic weather stations has enhanced surface observation coverage in remote areas, while also providing the framework for observational consistency. It is important to note that ocean-surface observations have greatly increased over the past decade, with further increases likely through organized international efforts such as the Global Ocean Observing System (GOOS). Such efforts include: i) expansion of the moored buoy networks that began with the TAO array ~10 years ago; ii) increases in observations from ships of opportunity, ocean-surface drifters and ocean profiling technology.

### 3.3 Observing-System Simulation Experiments (OSSEs)

THORPEX will carry out Observing System Simulation Experiments (OSSEs) that: i) provide information for the design of observing systems and observing networks; ii) provide an assessment of the potential for future observing systems and innovative uses of existing systems to achieve major improvements in forecast skill; iii) test advanced data assimilation methods; iv) assess the relative role of observations and ensemble forecasting in improving the utility of weather forecasts. The current methodology for performing OSSEs is designed to increase the realism and usefulness of such experiments. It consists of a long-time integration of an atmospheric simulation using a very-high-resolution state-of-the-art numerical model to provide a complete record of an assumed ‘true’ state of the atmosphere, referred to as the *nature run* or *reference atmosphere*. For the OSSE to be meaningful, it is essential that the nature run be carefully chosen, i.e. possess a model climatology, average storm tracks, etc., that agrees with observations as closely as possible within pre-specified limits. Nature runs will be performed from observed atmospheric initial states for a variety of flow regimes containing life cycles of high-impact weather systems. OSSEs will include an assessment of the potential impact of the emerging observing technologies and sensor deployments, described above in Section 3.1. This assessment requires accurate representations of the observing-system attributes, performance limitations, and observational errors. An important component of OSSEs, that improves the interpretation of their results, is validation against a corresponding Observing System Experiment (OSE) using real observations. In this regard, the accuracy of analyses and forecasts, and the impact of existing and emerging observing systems in the OSSEs, is compared with the corresponding accuracies and data impacts in operational forecasts. Ideally, the simulated and operational results should be similar. THORPEX observational campaigns (Section 3.4) will provide the OSE data sets for comparison with OSSEs.

### 3.4 Observing-System Tests, Regional Campaigns, and the THORPEX Global Prediction Campaign

The Observing-Systems Sub-program will contribute to coordinating and facilitating the logistics to test and evaluate experimental remote-sensing and *in-situ* observing systems in THORPEX Observing-System Tests (TOSTs), THORPEX Regional Campaigns (TReCs) and the THORPEX Global Prediction Campaign (TGPC).

**THORPEX Observing-Systems Tests** will test and evaluate experimental remote-sensing and *in-situ* observing systems, and when feasible, demonstrate their impact on weather forecasts. They will also be test beds for initial demonstrations of innovative uses of operational observing systems.

**THORPEX Regional Campaigns** are research and quasi-operational regional forecast demonstrations, of 1-3 month duration, contributing to the design, testing and evaluation of all components of interactive forecast systems. TReCs will be organised and coordinated by regional consortia of nations under the direction of regional THORPEX Science and Core Steering Committees (Asian, European, North-American, and Southern-Hemispheric). TReCs will likely address high-impact weather events, such as: i) arctic storms and cold-air outbreaks; ii) extratropical cyclones, and tropical cyclones transitioning into extratropical cyclones; iii) warm-season heavy precipitation over Asia associated with subtropical frontal disturbances and monsoon circulations; iv) large-scale convection over the Indian and Pacific Oceans, and its influence on atmospheric flows within tropical and extratropical latitudes. Researchers and forecast centres from all THORPEX nations will be encouraged to participate, at some level, in all TReCs.

**The THORPEX Global Prediction Campaign** will deploy the full suite of experimental and operational observing systems over the globe for a season to one year to establish the utility of interactive forecast systems to provide improved weather forecasts and user products. It will provide guidance through the WMO/WWW to agencies responsible for the design and implementation of the fixed and adaptive components of regional and global observing systems.

### 3.5 Proposed Research

The THORPEX Observing System Sub-programme will conduct the following research, logistical, and organizational activities:

**Develop and test new airborne delivery systems for deploying in-situ sensors:** These systems include: i) stratospheric balloons; ii) piloted and remotely-piloted aircraft; iii) rocketsondes; and iv) Bi-directional radiosondes. Systems (i-iv) will provide GPS radiosonde-technology dropsonde soundings over oceans and remote regions, e.g., the Tibetan Plateau; Polar regions.

**Carry out field-demonstrations of prototype remote-sensing systems for future airborne and satellite deployments:** This effort will include observations from airborne radiometers, scanning radars and lidars to obtain: i) individual remote-sensor profiles for comparison with simultaneous *in-situ* soundings; ii) area-averaged profiles that simulate existing and future satellite's field-of-view. The initial demonstrations will be through TOSTs within diverse geographical regions and meteorological conditions: a significant requirement for satellite remote sensing system calibration and evaluation.

**Coordinate the activities of the Observing System Sub-programme with the Data Assimilation and Observing Strategies Sub-programme:** This coordination will provide assistance in the development of advanced assimilation systems for the new observing systems. This includes the characterization of performance limitations, errors, and representivity of specific observing systems. This coordination is critical for carrying out effective OSSEs and their comparisons with OSEs, TOSTs, TReCs, and the TGPC.

**Organise the logistics and data management for TOSTs, TReCs, and the TGPC:** The resolution of logistical difficulties, such as air-traffic control clearance for deployment of *in-situ* sensors and the use of lidars in areas of aircraft flight routing will be the responsibility of this Sub-programme. Data-management will facilitate access to experimental and operational data sets, in real-time, and following field campaigns. The resolution of telecommunications

and data-quality issues early in the systems development is central to the real-time delivery of experimental data sets. THORPEX will strive to provide observations to operational NWP centres in real-time, at an appropriate resolution.

**Provide guidance to appropriate agencies on logistics of targeted observations:** The results of experimental and operational research demonstrations of targeted observing systems during THORPEX field programs will be provided to international and national meteorological agencies as input for consideration of adaptive programming of the global observing network. Adaptive programming could include: i) activation or repositioning of an existing satellite; ii) special satellite scanning schedules designed for high-time-resolution observations; iii) satellite spectral selection to facilitate testing of spatial density, frequency, and informational content; iv) the adaptive deployment of radiosondes, dropsondes, Aerosondes, and Driftsondes. Estimations will be made of the cost of various measurement approaches to assess the trade-offs between the cost of observations, observing strategies and the benefits to society.

### 3.6 Reference Material

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Velden, et al., 2003: The Burgeoning Role of Weather Satellites. Chapter 11 of the AGU book *Hurricane: Coping with disaster*. Robert Simpson, editor. pp 217-247.

The status and capabilities of current research and operational satellites can be found at:

<http://www.wmo.ch/hinsman/satopstatus.html> and <http://www.wmo.ch/hinsman/CGMShome.html>

## 4. Data Assimilation and Observing Strategies

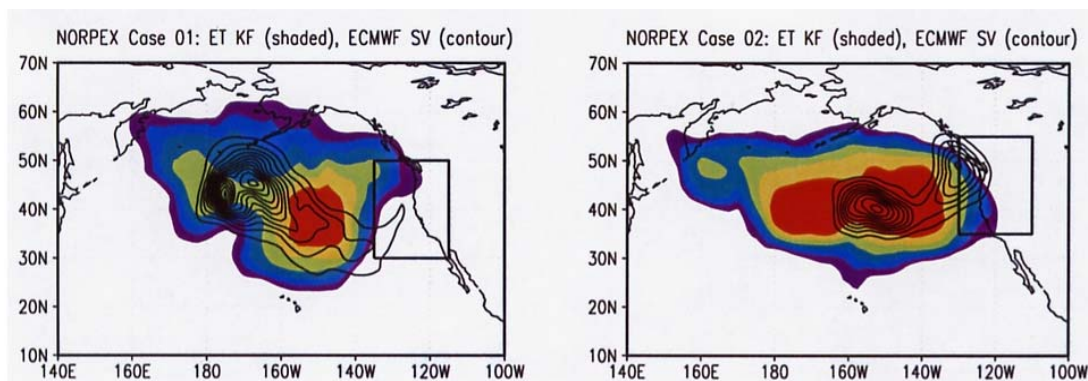
### 4.1 Rationale

*Data assimilation* is a process leading to both an estimate of the state of the atmosphere and ocean at a particular time, as well as a measure of the uncertainty associated with that estimate. This estimate may be used in a variety of contexts, such as: i) the initial conditions (i.e., the *analysis*) for a numerical weather forecast; ii) verification for a prior forecast; iii) to establish a record for climate studies. The estimate is derived from both observations and a first-guess (or *background*) short-range forecast from the previous analysis, along with the statistics of the errors (measures of uncertainty) associated with observations and the background. A significant component of forecast error originates from uncertainty in the initial condition. This uncertainty arises from uncertainties in the observations, the background forecast and approximations in the assimilation scheme. Recent advances in many aspects of data assimilation and observing systems provide the opportunity for making substantial improvements in forecast skill. These advances include: i) greatly increased volume and quality of atmospheric observations, e.g., from satellites; ii) adaptive observational techniques, or *targeting*; iii) improvements in assimilation algorithms, both in terms of their use of remotely-sensed observations and of their formulation. A program of research to capitalize on these advances is described below, under the headings: *targeting strategies*, *improved use of observations*, and *adaptive data assimilation*.

## 4.2 Targeting strategies

In the last decade, strategies were developed that use forecast-system information to identify locations where additional observations would provide maximal improvements in the expected skill of forecasts. We refer to these as adaptive, or targeted, observing strategies, commonly called *targeting*. Targeting identifies localized areas, referred to as *sensitive regions*, in which the quality of the analysis has the greatest expected influence on the subsequent skill of the forecast. Targeting strategies are based on techniques that predict, prior to the actual measurements, the influence of an observation (or set of observations) on a subsequent forecast, in a statistical sense. This prediction involves calculating how observations will influence analysis uncertainty and how analysis uncertainty will grow and evolve during the forecast. In practice, these calculations involve significant assumptions and approximations. This has led to a number of different targeting techniques; some involve the adjoint of the linearised version of the forecast model (Bergot et al. 1999; Montani et al. 1999; Gelaro et al. 1999) or of the assimilation scheme (Doerenbecher and Bergot 2001, Baker and Daley 2000), whereas others manipulate ensembles of forecasts (Bishop et al. 2001; Szunyogh et al. 2000).

Figure 4.1 illustrates two examples of regions targeted for additional observations in order to improve 24-h forecasts for the west coast of North America. This illustrates the differences that can arise in the location of sensitive regions depending upon the targeting strategy being used. Further research is needed to evaluate the performance of the various strategies. As the results of such evaluations are inherently statistical, they must be averaged over many cases. There is potential for further improvements of targeting strategies by relaxation of certain assumptions, such as linearization, and by the use of enhanced statistical information from advanced assimilation schemes.



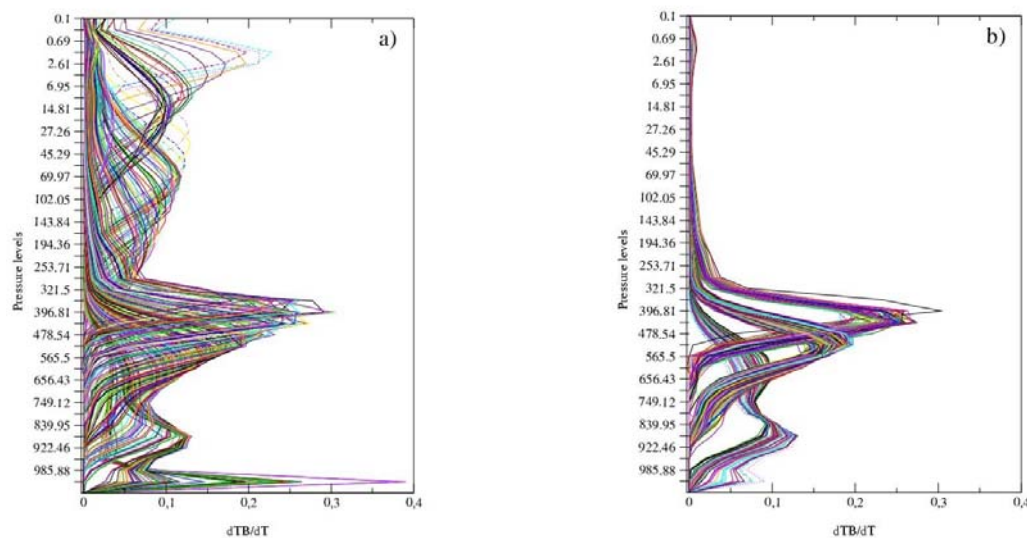
**Figure 4.1:** Illustration of the differences between the results arising from different targeting algorithms. Two cases from the NORPEX field experiment are shown; the intent is to select the observation location that will minimize the expected 24-h forecast error in the box at right. Colored regions indicate the sensitive regions as determined by an ensemble-based filtering approach; contours indicate region of increasing observation sensitivity as determined by an adjoint-based singular vector approach. From Majumdar et al., *QJRM*, **128**, p 2527.

Observing systems can be targeted in a variety of ways. Examples include the control of the sampling rate of satellite sensors or the timing and location of mobile upper-air soundings. Targeting techniques also have the potential for much broader applications. Besides providing guidance on where additional observations would be most effective for improving forecast skill, targeting can also be used to determine which observations are to be discarded, i.e., to conduct effective *thinning* of the observations. This capability will become increasingly more important, given the very large numbers of observations that will be

available from next-generation satellites. The ability to quantify the influence of a given observation on analysis or forecast uncertainty also provides the basis for assessing existing observational networks and providing recommendations for their future improvements.

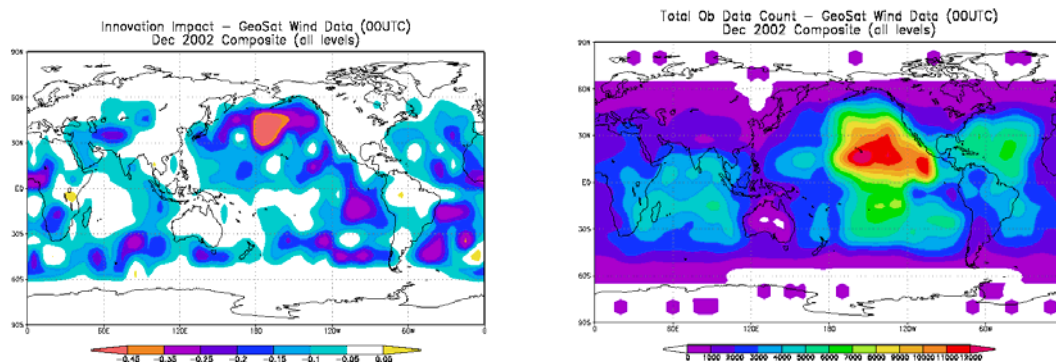
### 4.3 Improved use of observations

Forecast skill has significantly improved as the result of the development of innovative methods for assimilating observations. An example is the large benefit derived from assimilating radiances from satellites rather than the retrieved profiles. There are substantial opportunities to further improve the assimilation of observations, particularly those in sensitive regions. A key challenge will be to utilize effectively the large, and potentially overwhelming, volume of observations such as from next-generation satellites. One promising technique is to extract the most relevant information from high spectral-resolution sounders by selecting either specific channels or linear combinations of channels that contain the greatest independent information. Another approach is to use targeting to identify which subset of the total observational network is critical in determining forecast skill. Both of these techniques can be combined to target the most useful channels available from the high spectral-resolution channels. For example, Figure 4.2 shows examples of channel selections for the future advanced sounder IASI on board the European platform METOP. These 300 channels were selected out of 8461 for assimilation in a sensitive area. Panel a) presents the channels selected using an iterative method optimising the information extracted from the observations following Rabier et al (2002), and panel b) presents the channels selected using a method based on targeting principles following Doerenbecher and Bergot (2001). One clearly sees that the first method tries to improve the knowledge of the atmosphere throughout the pressure range, whereas the method focusing on sensitive structures mainly targets the low-level temperature.



**Figure 4.2:** Weighting functions as a function of pressure level of the 300 IASI channels selected for assimilation for a given profile in a sensitive area. Panel a) uses a channel selection method optimising the information content of the observations. Panel b) focuses on the retrieval of a sensitive pattern located below 300hPa through the use of a Kalman Filter Sensitivity approach (from Fourrié and Rabier, 2003).

Figure 4.3 presents an example where the largest reduction in forecast error arises from satellite observations in a sensitive region that does not coincide with the area containing the highest density of observations.



**Figure 4.3:** Left panel, estimated cumulative impact of all geostationary satellite wind observations (at 00UTC) on reducing December 2002 24-hr global forecast errors. Negative values indicate a reduction in forecast errors of combined temperature, wind, and pressure (all levels, units = J kg<sup>-1</sup>) due to assimilation of the wind observations. This calculation involves the adjoint versions of the NAVDAS 3d-Var assimilation procedure and NOGAPS forecast model. Right panel, total number of satellite wind observations during the same period. Figure courtesy of Rolf Langland (Naval Research Laboratory, Monterey, CA).

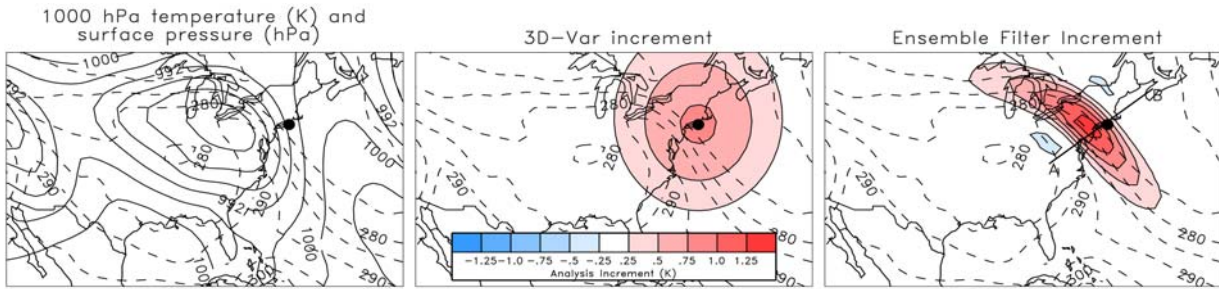
Another challenge is to quantify observation errors in terms of both their magnitude and covariances. Assimilation of high-resolution observations can degrade the analysis if their horizontal correlations are unknown and ignored. Other outstanding issues include specifying errors for moisture observations and characterizing representativeness errors, which arise when the measurements include scales or processes that are not represented in the forecast model.

It is believed that improved assimilation of precipitation and cloud processes will provide increases in forecast skill. Observations of these processes, such as from passive and active microwave sensors, are plentiful, but their use in the forecast system has been limited both because radiance/reflectivity is a not well known function of precipitation and cloud, and because the representation of precipitation and clouds in forecast models is poor. Improving and extending the use of cloud and precipitation observations may be crucial in the longer term.

#### 4.4 Adaptive data assimilation

There have been significant advances in the development of four-dimensional assimilation techniques, such as four-dimensional variational schemes (4D-Var) and the ensemble Kalman filter (EnKF). Such schemes are adaptive in the sense that they propagate information about background-error covariances and allow the influence of an observation on the analysis to depend on the evolving state of the flow and on the locations and uncertainties of past observations. These schemes also form the basis for techniques to quantify the importance of a given observation to future forecast skill, which underlie targeting strategies. Analysis and forecast experiments (Bergot 2001; Hamill and Snyder 2002; Desroziers et al. 2003) show that these techniques are more efficient than 3D-Var in extracting information from targeted observations. Figure 4.4 illustrates the importance of background-error covariances and the potential advantages of an adaptive assimilation scheme that incorporates flow dependence.

Techniques for introducing flow-dependence into data assimilation range from simple and computationally-inexpensive modifications of covariance models in existing algorithms to



**Figure 4.4:** Illustration of the impact of background-error covariances. The surface pressure and 1000 hPa temperature of the model first guess are shown in the left-hand panel. Consider the correction, or “increment,” to an observation that is 1K warmer than the first guess at the location denoted with a dot. 3D-Var increments (middle panel) are isotropic, largest at the observation location and smaller with increasing distance from the observation. Ensemble-filter increments use flow-dependent background-error covariances that recognize that errors are more strongly correlated along the warm front than across it; hence corrections are stretched out along the frontal zone and maximized not at the observation location, but nearby where the gradient is tightest (courtesy of Tom Hamill).

more complex approaches, such as 4-D Var, reduced-rank Kalman filters and the EnKF. These computationally more expensive techniques approximate both the flow-dependent growth of forecast covariances and their reduction from the assimilation of new observations. More general ensemble-based techniques such as particle filters or Bayesian learning algorithms may provide methods for dealing with poor performance in highly nonlinear regimes. There is also potential to use statistical information provided by adaptive assimilation schemes to improve other aspect of the assimilation process, such as quality control.

Finally, as both observations and assimilation methods are improved, uncertainties in the forecast model will impose limits on the assimilation process. Accounting for this model uncertainty in the assimilation will then be crucial, particularly for adaptive schemes that use the forecast model for estimates of the background error covariances. More generally, the importance of quantifying forecast errors arising from uncertainties in both initial condition and the forecast model provides a strong link to the Predictability and Dynamical Processes Sub-program research (Section 2).

## 4.5 Proposed Research

The following research activities will focus on developing the required advances in the use of observations, targeting methods and data assimilation:

### *Improved use of observations*

**Quantify observing-system errors:** Estimate observation errors, especially errors of representativeness, which are likely to be flow-dependent and correlated between nearby observation locations. Test the effects of improved observation-error statistics on forecast skill.

**Develop methods for efficient utilization of high-volume datasets:** Develop and test adaptive methods for thinning large datasets so that the most useful observations are retained. Develop techniques for assimilating high-resolution observations, including proper characterization of horizontal correlations and averaging (or *super-obsing*) of nearby measurements. Develop techniques to extract the maximum information content from hyper-

spectral sounders, and other observing systems when, for example, it is computationally impractical to assimilate radiances from all channels.

**Improve the use of geostationary satellite observations:** Improve the use of visible, infrared and water vapour image-sequences to infer wind information. This may require innovative approaches, such as interactive height assignment methods or the use of imagery sequences directly in the assimilation.

**Improve assimilation of physical processes:** New methods to assimilate certain satellite observations (e.g., those from active microwave sensors and cloud and precipitation imagery) are required in order to infer physical processes such as diabatic heating.

### *Targeting techniques*

**Refine targeting strategies:** Perform observing system experiments (OSEs) and observing system simulation experiments (OSSEs), including demonstrations with data sets from field experiments, to evaluate the performance of targeting strategies. This evaluation will lead to refinements in targeting strategies.

**Generalise existing targeting techniques:** Account for non-linearity and non-normality, especially for longer forecast lead times (>2-3 days) and/or in flow regimes where physical processes such as moist convection and clouds play a dominant role.

**Test targeting algorithms for a wide range of weather systems:** Candidate forecast problems include: i) hurricane track and intensity forecasts; mid-latitude summer heavy rainfall episodes; iii) and extended range (week-two) predictions. This should include research on the dynamical processes that propagate information spatially and temporally between the targeted regions and the selected weather events.

**Support TOSTs, TReCs and the TGPC:** Provide guidance for the deployment of individual and composite (multi-sensor) observing systems during THORPEX Observing System Tests (TOSTs), THORPEX Regional Campaigns (TReCs), and the THORPEX Global Prediction Campaign (TGPC).

**Design observational networks:** Develop and test systematic and objective techniques for the design of observing networks. Quantify the required accuracy and resolution for the measurement of various quantities, and evaluate trade-offs between accuracy and resolution, or between resolution and areal coverage.

### *Adaptive data assimilation*

**Improve background-error covariances in existing assimilation schemes:** Test improved, flow-dependent models of background-error covariances in techniques like 3D-Var and 4D-Var.

**Develop methods for cycling flow-dependent background errors:** Develop and test assimilation methods that explicitly allow for changes in background-error covariances from one analysis to the next, such as Kalman-filter/4D-Var hybrids or ensemble-based schemes.

**Develop adaptive quality control:** Develop and test adaptive quality control algorithms that can utilize information provided by flow-dependent background-error covariance estimates.

**Incorporate model uncertainty into data assimilation procedures:** Develop and test ways of incorporating the effects of model uncertainties leading to systematic forecast errors and the effects of unresolved scales into the specification of background-error covariances for data assimilation schemes. Develop statistical algorithms to “tune” model uncertainty in assimilation algorithms and to diagnose and correct model bias.

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## 5. Societal and Economic Applications

### 5.1 Rationale

Weather forecasts provide timely information about atmospheric conditions that affect society and the economy. Skillful forecasts allow society to mitigate the consequences of high-impact weather and to take efficient advantage of day-to-day weather. Many applications of weather forecasts involve translating predicted meteorological parameters

(e.g., wind speed; temperature; precipitation) into societal/economic attributes of the natural or human environment (e.g., energy demand; transportation efficiency; demands on health services; water resources; pest infestations; air quality), as well as providing forecast information on relevant spatial and temporal scales. It is important for weather forecast products, derived from meteorological parameters, continue to meet the diverse applications and the needs of society, as weather-forecast capabilities and societal needs evolve.

THORPEX Societal and Economic Applications (SEA) research will contribute to the development of forecast systems that are responsive to the needs of users of weather-forecast information, with an emphasis on *high-impact weather forecasts*. These forecasts include predictions of extreme weather hazards associated with weather systems such as tropical cyclones and winter storms, as well as non-extreme weather, e.g., periods with unanticipated above or below average temperatures or precipitation. High-impact weather forecasts are defined by their effect on society and the economy; and more specifically, on the diverse sectors that utilize weather information. These sectors include: emergency management; food production; water management; private sector providers, health services; energy; tourism and leisure; transportation; the general public. SEA research will assess how weather forecast information is utilized by various sectors of society and the economy and how this use could be improved. This will involve identifying what constitutes high-impact weather forecasts, and estimating economic and societal value of weather information. The research results will include both proposed changes to forecast systems (e.g., targeted meteorological observations and/or tailored ensemble members, for specific high-risk sectors) and new methods for extracting user-relevant products from weather information. In addition, the SEA Sub-programme will determine the potential added value to society, if these proposed changes and new products were implemented in operational practice.

From an economics perspective weather forecasting is an *infra-technology* producing valuable information for economic and technological activities (Williams and Smith 2003). The impact of weather forecasts on societal and economic activities is a consequence of the following forecast elements: i) *content*: relevance of product information to the users; ii) *distribution*: product dissemination on a time scale sufficient for action; iii) *communication*: product format that users can comprehend and interpret; iv) *recognition*: recognition by users that the information has value; v) *response*: actions taken by users in response to the information. These elements are links along a chain of action. If any one link is broken, then the impact and the value of the forecast information will be diminished. SEA research will identify weaknesses in these links, enabling development of new methods for enhancing societal and economic use and value of weather information.

Relevant references that provide an overview of societal economic research are found in Section 5.4

## **5.2 Societal and Economic Benefits of Weather-Forecast Information**

There are benefits to industries and markets derived from use of weather forecast information. Examples include the use of weather products that provide improvements in: i) efficiency of energy production and transmission to meet energy demand; ii) protection of infrastructure and positioning of utilities and emergency-preparedness equipment; iii) efficiency of agricultural production processes (e.g., planting, harvesting, and freeze mitigation); iv) planning and allocation of resources by travel and leisure industries; v) routing for land, sea, and air transportation and the distribution of materials, livestock and people; vi) allocation of health service resources to target weather-sensitive conditions, such

as influenza and asthma; vii) allocation of resources to target transmission of plant, animal or human diseases; ix) management of water resources. For the performance of commodity markets (energy, agricultural and industrial), market-relevant weather information can be used to influence strategies adopted by different companies within a given market to regulate the performance of others, e.g., producers; suppliers; purchasers.

Many assessments of the value of weather forecast information currently address cases of idealized users such as those who make *binary decisions*, e.g., whether or not to protect a crop or de-ice a motorway. In addition, the value of weather information has been assessed only for a relatively limited set of users. SEA research will extend such value assessments to a broader set of situations, decision types, and user sectors, using a variety of methods. This will include addressing outcomes that involve continuous variables, such as the quantity of electricity to be generated. Together, these assessments will contribute to the improved use and value of forecast products and the design of forecast systems. As an example, knowledge of the societal and economic value of weather information can influence decisions regarding the allocation of observational, computational, and research resources. These decisions include: i) forecast-model computational resolution versus number of ensemble forecast members; ii) targeted versus non-targeted observations; iii) standard or rapid update of the data-assimilation cycle. Knowledge that the forecast system itself is responsive in this way will enhance both the participation and the degree of feedback from users and providers of weather forecast information.

There are benefits to society from mechanisms that enhance and enforce mitigating actions, and the benefits to be gained from proper anticipation of weather conditions and that ensure that those who could have taken mitigating action, given prior warning, indeed do so. This includes proceeding beyond the design, implementation and assessment of responses to weather warnings, into guiding policy guidelines for initiation of legal actions in the event of criminal or civil negligence, given sufficient lead-time prior knowledge on the likelihood of such high-impact events.

A key aspect of SEA research is to develop a framework within which researchers in the meteorological, economic, policy and social sciences will interact with operational forecast centres and users of weather forecast information. This interaction will contribute to the development of improved forecast systems designed for the diverse geographic regions involved in THORPEX. Research findings will be made available for training and educational material to all nations.

### **5.3 Proposed research**

THORPEX SEA research will: i) identify high-impact weather forecasts; ii) assess the impact of improved forecast systems; iii) develop advanced forecast verification measures; iv) estimate the cost and benefits of improved forecast systems; v) enable the development of new user-specific products; and vi) facilitate the transfer of THORPEX advances to forecast centres throughout the world. This research will be conducted through collaboration with forecast *providers* (e.g., operational forecast centres; private-sector forecast offices) and forecast *users*, e.g., energy producers and distributors; transportation industries; agriculture producers; emergency management agencies; and health care providers. It will provide wide-ranging information on what constitutes high-impact weather forecasts for individual sectors and users, and influence research priorities within all THORPEX Sub-programmes.

The THORPEX Societal and Economic Application Sub-programme will conduct research to:

**Identify high-impact weather forecasts:** This effort will identify the global-to-regional weather forecasts that have major effects on selected sectors of society and economies within various geographical regions. It will address the effects of recent high-impact weather forecasts, and the *economic consequences* (e.g., property damage; loss of crops and/or livestock; interruption of transportation services) and *human consequences*, e.g., personal injury, illness from heat/cold; contamination of drinking water by floods; damage to electric power distribution. Studies will investigate which forecast improvements would be of the greatest *marginal value*, e.g., the greatest added value to the users and society in mitigating losses, increasing gains, or otherwise improving the management of resources. Evaluations will be made of the accuracy of forecasts and responses to subsequent weather forecast products and the value of potential improvements will be assessed from the perspective of a range of current and potential weather-sensitive sectors.

**Assess the impact of improved forecast systems:** The above identification of high-impact weather forecasts will provide the basis for estimating the marginal value of improvements to forecast systems. Studies of marginal improvements to forecast systems will be made for: i) various types of weather forecasts and lead times; ii) diverse user groups or societal/economic sectors; iii) different geographic regions. Estimates will be made of the marginal value of improved weather forecast information from databases, such as: i) archived forecasts for past weather events; ii) Observing System Simulation Experiments (OSSEs); iii) forecasts from THORPEX field campaigns. These studies will estimate the range of marginal gains to be derived from a variety of forecast system improvements within different sectors of society

**Develop advanced forecast verification measures:** The development of user-relevant verification of weather forecast information is a prerequisite to evaluating the societal and economic impact of improved forecast systems. Many of the current verification measures used by operational forecast centres to evaluate forecast skill, e.g., 500-mb anomaly correlations between the model forecast and the model analysis, are of limited value to those who use weather forecast information to make decisions for the benefit of society and economies. The appropriate verification measures vary with the user's requirements. *User-relevant forecast measures* include: i) site- and time-specific measures (e.g., time of passage of a front; transition from rain to frozen precipitation; timing of air pollutants above/below critical concentrations); ii) integrals over space and time, e.g., transportation travel times; power-generation efficiency; hours of air pollutants above critical concentrations; duration of hazardous high or low temperatures. Such measures are often a nonlinear function of multiple meteorological variables (e.g., wind speed; temperature; humidity; visibility; sea state) and non-meteorological variables e.g., type of equipment in place; topography; land use. The advanced verification measures developed within this Sub-programme will be used by other THORPEX Sub-programs and by operational forecast centres to evaluate forecast-system improvements using methods that are relevant to the value that a range of users derives from forecasts.

**Estimate costs and benefits of improved forecast systems:** Estimating the costs and benefits of implementing potential THORPEX advances in daily forecast operations will require: i) estimating potential forecast improvements from various forecast system implementations; ii) estimating marginal costs and benefits of the improvements; and iii) combining this information in a way that can be used in making decisions on the design of

forecast systems. In order to provide these estimates, the SEA Sub-programme will build on existing methods for evaluating costs and benefits, using the information provided by the SEA research described above. The Sub-programme will also identify the information from other Sub-programmes required to develop such estimates, e.g., detailed estimates of costs of implementing different observing systems; a comprehensive evaluation of expected forecast improvements, measured with user-relevant verification measures.

**Develop new user-specific weather products:** THORPEX SEA research will develop new methods to translate predicted meteorological parameters into quantities of interest to specific user sectors, so that improvements to forecast systems will be responsive to society's diverse weather information needs. This will include developing methods where the outcomes of interest to users are continuous functions of meteorological conditions and where operational probabilistic forecast information can be utilized. Studies on improvements in current probabilistic forecast systems will provide information on multivariate, spatial and temporal information critical to many social and economic applications. In addition, SEA research will develop methods to overcome current barriers to improved use and value of weather forecast information, e.g., difficulties utilizing probabilistic forecasts in decision-making; warnings integrated over space or time scales incommensurate with user requirements.

**Facilitate transfer of THORPEX advances to forecast centres throughout the world:** The SEA Sub-programme will facilitate the transfer of THORPEX research findings on the use of advanced weather forecast information to user sectors and forecast providers throughout the world, with a special emphasis on developing countries. This will include assisting in training in the use of the new methods developed by SEA research. In addition, SEA techniques and evaluations of forecast systems will be provided to governments and international agencies to assist with decisions about allocations of resources for improved weather services. The transfer of THORPEX research findings will not only benefit societies and economies throughout the world, but will also increase public awareness of the value of weather forecast information to society and economies.

## 5.4 Reference Material

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